# Energy Based Aerodynamic Modeling: Increasing Fidelity of Fixed-Wing Constructive Entities

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## ABSTRACT

Distributed Mission Operations (DMO) is an ideal setting for practicing Beyond Visual Range air-to-air tactics. Hardware and software limitations often dictate the use of simplified aerodynamic models for control of fixed wing constructive entities within synthetic environments**.** In many tactical situations the long range fight will disintegrate into close-in air combat, which for a variety of reason is difficult to represent in virtual simulators. The eXperimental Common Immersive Theatre Environment (XCITE) developed at Warfighter Readiness Research Division (AFRL/HEA) was designed to provide a physics based high-fidelity threat environment for training and rehearsal in a DMO environment. Feedback by operational pilots identified unrealistic constructive flight performance as a critical shortfall of XCITE.

Here we will discuss the development, testing and validation of an energy based aerodynamic model in an effort to provide a more effective threat environment for DMO. Specific Excess Power ($P_s$) tables were created using thrust, drag, lift and loading data for each aircraft; these tables then provide accurate acceleration figures that are feed back into the original aero-model. In testing, aircraft flight performance was compared against data obtained from aerodynamic models in both 6-DOF Full Mission Trainers and the baseline XCITE aero model.

## 1 INTRODUCTION

This paper will explore the development, integration, and testing of an enhanced aero-model for the eXperimental Common Immersive Theatre Environment (XCITE) developed at the Warfighter Readiness Research Division (AFRL/HEA) in Mesa, Az. This system was developed to use Defense Intelligence Agency (DIA) approved data in the form of engineering reports developed at the National Air and Space Intelligence Center (NASIC). This enhanced aero-model uses lookup tables to correlate fixed wing constructive entity flight performance with that of the actual aircraft.

## 2 BACKGROUND

Distributed Mission Operations (DMO) is the cornerstone of the Air Force training transformation. Combining live, virtual, and constructive entities together in a distributed synthetic environment allows the warfighter to maintain combat readiness by conducting mission rehearsal in operationally realistic environments. Beyond Visual Range (BVR) air-to-air combat has been the focus of initial Air Force DMO efforts for several reasons. First and foremost this is the arena that the USAF seeks to dominate in order to achieve Air Superiority over the battlefield. Above and beyond the tactical and doctrinal issues that lead to a BVR-centric DMO environment several technical issues also contributed to this focus. A long range aerial engagement does not have the same out-the-window visual fidelity requirements as air-to-ground or close-in "fur-ball" aerial engagements. DMO provides the ideal setting for training on radar mechanization and tactics employment in a BVR fight. Additionally, DMO provides ample data for debrief such as time spent in weapon engagement zones, radio communication between wingmen and Air-Battle Managers, etc. Unfortunately, current virtual trainers cannot accurately replicate the physiological factors involved in high "*g*" aerial combat maneuvering leaving live-flight the optimum medium for training such skills.

Developed to provide a robust Electronic Warfare (EW) training environment complete with high-fidelity radar and jammer models, XCITE's original design did not call for a high performance flight model. A simple aero-model would suffice for the BVR engagements trained for in DMO, therefore a 3-DOF maneuvers model was used to control the constructive fixed-wing entities within XCITE. This model, though sufficient for basic navigation and control of non-maneuvering targets, was found to provide unrealistic flight performance, primarily a lack of energy

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14. ABSTRACT
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15. SUBJECT TERMS
**DMO, aerodynamics, constructive entities, energy maneuvering, specific excess power; Aerodynamic models; Energy based dynamic model; Next Generation Threat System; NGTS;**

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bleed-off during aggressive maneuvers. This deficiency was identified as a critical shortfall and put at the top of the upgrade "wish-list" by the operational warfighters, AFRL/HEA set to work to provide an upgraded aero-model for XCITE.

The span of fidelity in aero-models in a computer generated force simulator ranges from the original XCITE simplistic maneuvers model to ultra high-fidelity models which calculate, in real-time, force and moment build up due to control surface deflection and calculation of control and stability derivatives. Working under the constraints of providing a higher fidelity flight model that would not significantly lower entity count yet easily be incorporated into the existing routine structure, it was determined that an energy maneuvers flight model would provide the proper mix of fidelity and ease of integration.

The term "Energy Maneuverability" is attributed to the work of Col John Boyd [Hehs, 1998]. Developed as a means to quantify an aircraft's agility, energy maneuverability refers to an assemblage of several performance characteristics including; sustained *g* capability (a measure of an aircrafts ability to turn without losing airspeed or altitude), instantaneous *g* (also a measure of an aircraft's ability to turn but without regard to loss of airspeed), and Specific Excess Power ($P_s$) (describes an aircraft's potential to climb, turn, or accelerate at it's current fight condition). Specific Excess Power is the primary driver for describing an aircraft's flight performance. At positive values of $P_s$ an aircraft is free to turn, climb or accelerate, when $P_s$ is negative an aircrafts is forced to decelerate or dive or a combination of both. A maneuvering, turning, aircraft will reach its maximum sustained turned capability when its specific excess power falls to zero. Specific excess power is also useful to depict an aircraft's speed-altitude envelope, if $P_s$ has reached zero, then the aircraft can no longer climb nor accelerate thus the aircraft has reached either its ceiling or maximum level velocity. One can easily see the power of Boyd's energy maneuverability theory in describing an aircraft's flight performance and the need to accurately model an aircraft's $P_s$ in order to faithfully replicate that aircraft's performance.

## 3 METHODS

### 3.1 Specific Excess Power Tables

Now that the theory and principle of energy maneuvering has been introduced it is necessary to describe the engineering approach taken to develop the specific excess power tables. The total energy (TE) of an aircraft in flight is composed of its kinetic (KE) and potential (PE) energy [Olson, 2000], where PE is a function of the aircraft's weight and height, or altitude, and KE is a function of its weight and velocity. This relationship is illustrated below in Equation (1):

$$TE = PE + KE = Wh + \frac{1}{2}\frac{W}{g}V^2 \qquad (1)$$

| Where: | | | |
|---|---|---|---|
| | W | weight | lbs |
| | h | height | ft |
| | g | gravitational acceleration | ft/s$^2$ |
| | V | velocity | ft/s |

As shown in Equation (2), the total energy is divided by the weight of the aircraft yielding specific energy, also known as energy height. By normalizing this parameter is it now possible to accurately compare the performance of aircraft of vastly differing weights.

$$h_e = \frac{TE}{W} = h + \frac{1}{2}gV^2 \qquad (2)$$

Power is defined as the time rate of energy change, specific power is found by taking the time derivative of the specific energy [*Naval Test Pilot School Flight Test Manual, Fixed Wing Performance*, 1997]. An aircraft's power can also be described as the difference between its thrust and drag multiplied by velocity; this can be seen in Equation (3) below:

$$P = \frac{\partial h_e}{\partial t} = V(T - D) \qquad (3)$$

| Where: | | | |
|---|---|---|---|
| | P | power | ft-lb/lb-s |
| | V | velocity | ft/s |
| | T | thrust | lbs |
| | D | drag | lbs |

Normalizing the power equation by dividing by weight yields the basic equation for specific excess power [Raymer, 1999], as seen in Equation (4).

$$P_s = \frac{V(T-D)}{W} = \frac{\partial h_e}{\partial t} + \frac{V}{g}\frac{\partial V}{\partial t} \qquad (4)$$

Equation (4) provides the foundation for the data used for the upgraded aero-model. However, to obtain the detailed and platform specific information used here we must expand and manipulate the terms. The first iteration merely rearranges Equation (4) by grouping like terms and factoring out velocity, drag is also expanded into its individual components:

$$P_s = V\left[\frac{T}{W} - \frac{D_o}{W} - \frac{D_i}{W}\right] \qquad (5)$$

Where: $D_o$ parasitic drag lbs
$D_i$ induced drag lbs

These two drag terms are further expanded as seen in Equations (6) and (7) into coefficient form:

$$D_o = C_{D_o} \tfrac{1}{2}\rho V^2 S = C_{D_o} qS \qquad (6)$$

$$Di = C_{D_i} \tfrac{1}{2}\rho V^2 S = C_{D_i} qS \qquad (7)$$

Where: $C_{Do}$ parasitic drag coefficient
$C_{Di}$ induce drag coefficient
ρ air density slugs/ft$^3$
S wing area ft$^2$
q dynamic pressure lbs/ft$^2$

Substituting Equations (6) and (7) into Equation (5) yields Equation (8), seen below:

$$P_s = (V)\left[\frac{T}{W} - \frac{C_{D_o} qS}{W} - \frac{C_{D_i} qS}{W}\right] \qquad (8)$$

With the given data it was necessary to further modify Equation (8) to allow specific drag data from each aircraft to be incorporated. Velocity is now represented by Mach number and the speed of sound while the coefficient of lift has been incorporated to balance the induced drag portion of the equation:

$$P_s = (MC)\left[\frac{T}{W} - \frac{C_{D_o} qS}{W} - \frac{\left(C_{D_i}/C_L^2\right) C_L^2 qS}{W}\right] \qquad (9)$$

Where: M mach number
C local speed of sound ft/s
$C_L$ coefficient of lift

The last step in developing the $P_s$ tables is expanding the coefficient of lift term to take into account the load factor [Raymer, 1999]. In Equation (10) the formula for lift is squared to compensate for the $C_L^2$ term found in the given induced drag data.

$$C_L^2 = C_L \times C_L = \left(\frac{L}{qS}\right)^2 = \left(\frac{nW}{qS}\right)^2 \qquad (10)$$

Where: n load factor

The final iteration of the specific excess energy equation, Equation (11), yields a relatively easy means of developing data tables, via EXCEL spreadsheets that incorporate the necessary parameters (i.e. thrust, weight, drag, load factor, wing area, Mach number, and dynamic pressure) to produce accurate $P_s$ data.

$$P_s = (MC)\left[\frac{T}{W} - \frac{C_{D_o} qS}{W} - \frac{\left(C_{D_i}/C_L^2\right) n^2 W}{qS}\right] \qquad (11)$$

Table (1) shows sample output data from Equation (11) at a load factor of 1. At a quick glance one can visualize the speed-altitude envelope.

**Table 1-**Sample Specific Excess Power (ft/s) at n=1

| Mach | Sea Level | 10K ft | 20K ft | 30K ft | 40K ft |
|---|---|---|---|---|---|
| 0 | -37 | -162 | -315 | -525 | -860 |
| 0 | 206 | 65 | -65 | -213 | -420 |
| 0 | 405 | 226 | 76 | -70 | -246 |
| 0 | 599 | 376 | 190 | 32 | -142 |
| 1 | 776 | 532 | 301 | 116 | -62 |
| 1 | 946 | 691 | 410 | 193 | 6 |
| 1 | 1061 | 831 | 538 | 283 | 78 |
| 1 | 1118 | 966 | 671 | 374 | 149 |
| 1 | 1165 | 1114 | 843 | 502 | 237 |
| 1 | 1139 | 1258 | 1026 | 640 | 330 |
| 1 | 1068 | 1381 | 1153 | 807 | 444 |
| 1 | 950 | 1495 | 1277 | 986 | 566 |
| 1 | 834 | 1515 | 1361 | 1078 | 734 |
| 1 | -1538 | 1509 | 1433 | 1167 | 832 |
| 2 | -1885 | 1332 | 1375 | 1215 | 889 |
| 2 | -2281 | -1530 | 1287 | 1252 | 940 |
| 2 | -2730 | -1829 | 1217 | 1201 | 940 |
| 2 | -3234 | -2165 | 1042 | 1130 | 930 |
| 2 | -3798 | -2540 | -1642 | 1059 | 869 |
| 2 | -4424 | -2957 | -1909 | 884 | 827 |
| 2 | -5116 | -3418 | -2204 | 528 | 674 |
| 2 | -5876 | -3924 | -2528 | 128 | 498 |
| 2 | -6709 | -4479 | -2883 | -1807 | -1125 |
| 2 | -7617 | -5084 | -3271 | -2047 | -1270 |

The spreadsheets are easy to manipulate and can easily be changed to represent different load factors, weapon load-outs, weight, etc. Table (1) was produced using sample data and does not represent any specific aircraft.

Now that $P_s$ data is available for each platform it can now be used to determine performance characteristics. Using data from Table (1) at Mach .9 at sea level we have a $P_s$ value of 1,165 ft/s, using Equation (4) and assuming the aircraft does not change altitude, the aircraft has enough energy to accelerate at 37.3 ft/s$^2$. Similar calculations can be made to determine maximum climb angle by assuming flight path acceleration is zero and all available $P_s$ is converted into vertical velocity. With the raw $P_s$ data at hand the next step was to incorporate this new data into the existing control laws, subroutines, and tactics found in XCITE.

## 3.2 Integration into XCITE

An energy based aerodynamic model was selected for its balance between reasonably-close aircraft performance and limited CPU usage. Within XCITE the flight maneuvers and aero-model were completely intertwined with one another. Each tactic, from a simple turn to a complex posthole maneuver, basically had its own albeit simple aero-model.

The legacy hybrid maneuvers / aero-model in XCITE, or Maneuvers Model, is a time-based system. Meaning after an aircraft is assigned a tactic a series of pitch, roll and speed changes are planned for the aircraft at a single instance and then stored sequentially in an array with corresponding time durations. The data stored in the maneuvers array is used to populate the entity in the visual system and to move the aircraft through space. The aircraft completes the first element of the array for X seconds, completes the next element of the array for Y seconds, and so on. After the first call to the tactic, there is no check to see whether or not the aircraft can in fact continue to perform the tactic as its energy state changes. The initial instance of populating the array must be perfect for the entire flight condition of the tactic in order for the aircraft to fly realistically. Although reasonably accurate for navigation and mild maneuvers, the Maneuvers Model is prone to substantial error in any tactic that involves aggressive changes in heading, velocity or altitude.

The original aero-model incorporated into XCITE controlled all aspects of flight with three main maneuvering subroutines. These crucial routines handled altitude control, heading control, and velocity control. Tactical routines called these main subroutines as needed to perform the combination of climbing, diving, turning, and accelerating needed to perform the tactical maneuver. For simplification, the Maneuvers Model in XCITE calculates the aircraft's movements linearly checking placard aircraft limitations such as minimum airspeed, maximum airspeed, and maximum ceiling. Engine and lift performances are never checked against the atmospheric conditions. Each aircraft type has its own sustained and max-*g* capability turns, but those values do not vary within the aircraft's speed-altitude envelope. Additionally, the system imposes arbitrary climb & descent angles and acceleration & deceleration rates independent of the aircraft type or energy state.

The energy based aerodynamic model was molded into the existing Maneuvers Model to create an Energy Maneuvers Model. It is not a full-fledged aero-model; it merely places checks and balances onto the existing system so the aircraft will perform more realistically. The Energy Maneuvers Model, which is composed of two parts, and the Maneuvers Model are illustrated in Figure (1).

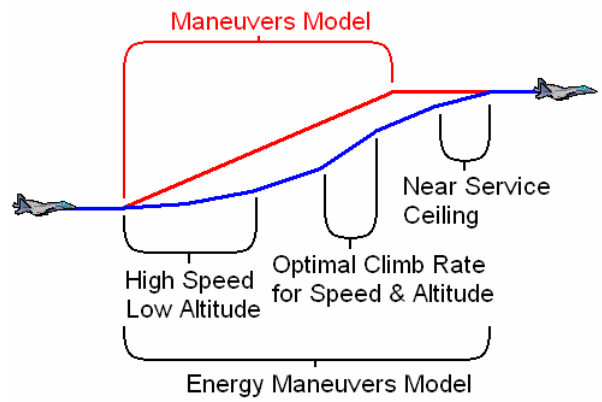

**Figure 1**- XCITE Aero-Model Climb Comparison

The first part involves placing performance limitations on the aircraft. The Energy Maneuvers Model contains code for each tactic that retrieves the specific excess power of the aircraft at its current altitude, Mach number, and *g*-loading (load factor), then adjusts the climb angle, turn angle, and rate of acceleration based on its specific excess power data-tables.

The second part involves revisiting the tactic. With only a few exceptions, the current Maneuvers Model has the tactic function called only once to fill the maneuvers array. The Energy Maneuvers Model will re-call the tactic function, at a predetermined heartbeat, to ensure the aircraft is performing in accordance with its current energy state. The duration between re-calls to the tactics is adjustable in the source code if a higher fidelity model is requested and the computational power is available.

# 4 TESTING

A multi-pronged approach was used to test the upgraded aero-model. The two main concerns were whether there was a substantial strain on the processor with a related negative affect on entity count and how well the model simulates actual aircraft performance. As for aircraft performance testing, this was accomplished over several steps. This first step was to compare $P_s$ values found in the specific excess power data-tables to DIA approved data found in the NASIC Engineering Reports [*Engineering Report: F-16C Block 30 Analysis,* 1993]. Once the specific excess power data tables were found to correlate with the DIA data, the next step was to ensure the subroutines developed translated the validated $P_s$ data into accurate flight performance. Aircraft were instructed to perform basic climb, turn and acceleration maneuvers to compare performance against DIA data. Finally, positional and velocity profiles of aircraft performing offensive and defensive tactical maneuvers were compared against output of a high-fidelity F-16C Full Mission Trainer.

# 5 RESULTS AND ANALYSIS

## 5.1 Computational Testing

Figure (2) shows a comparison between the Energy Mode on (upgraded energy based aero model) and Energy Mode off (legacy aero flight model originally found in XCITE). The CPU performance test was conducted at a worst case scenario for the Energy Maneuvers Model by commanding all the entities to climb simultaneously. Thus, all entities would revisit their tactic in the same frame, causing the most CPU drain.

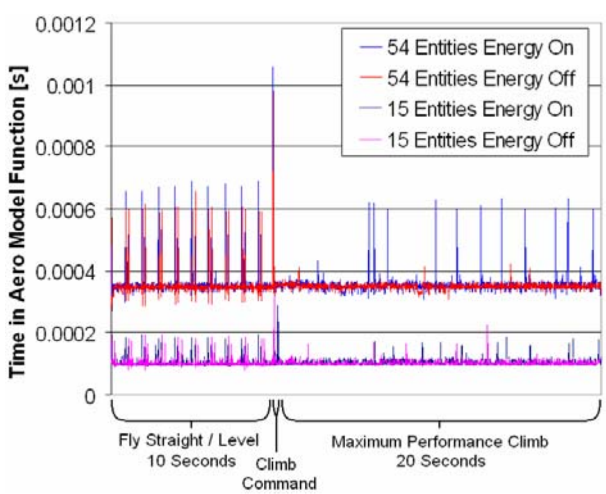


**Figure 2**-CPU Performance Test Comparison

The periodic spikes prior to the climb command are a result of the fly tactic re-calling itself with both the Energy Mode on and off. Both the 15 entity scenario and the 54 entity scenario displayed prominent spikes as expected when the climb command was issued. Following the spike, the Energy Mode off cases never revisited their tactics and therefore used very little CPU. With only 15 entities, the Energy Mode on showed little to no difference compared to Energy Mode off. The 54 entity scenario on the other hand showed the CPU spikes when all entities were revisiting the climb command.

Overall, the addition of the Energy Maneuvers Model had little affect on the total number of constructive entities XCITE was able to support simultaneously. Despite the addition of look-up energy tables and periodically readjusting the aircraft's flight, the Energy Maneuvers Model used negligibly more CPU time than the existing Maneuvers Model. Flying straight and level was actually harder on the CPU then the climb maneuver. In most scenarios it is unlikely that very large numbers of aircraft would receive simultaneous commands, therefore the Energy-On re-call spikes would be distributed.

## 5.2 Performance Testing

Due to the wealth of information, clear NASIC reports, Full Mission Trainer (FMT), and multiple Subject Matter Experts the F-16C was used as the primary aircraft while undergoing performance testing on the upgraded aero model. Figure (3) depicts the Energy Maneuverability at 1-*g* of a Block 30 F-16C found in the F-16C NASIC Engineering Report. The first step in evaluating the flight performance of the upgraded aero-model was to ensure the $P_s$ values closely matched that of the actual aircraft. The specific excess power tables, as seen in Table (1) were transferred into contour plots and then compared against the NASIC contour plots of each aircraft.

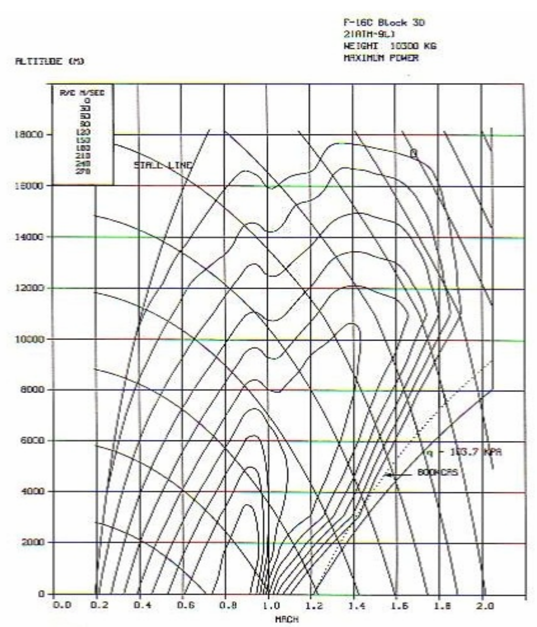


**Figure 3**-NASIC Energy Maneuverability Contour Plot (1-*g*)

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Typical $P_s$ contour plots for fighter type aircraft have several common characteristics. Lines of equal $P_s$ tend to compress at low altitudes at the area immediately behind the sound barrier to the aircraft's limiting speed. $P_s$ is always highest at sea-level at around Mach .85, where the drag is low and thrust is high. Lines of equal excess specific power will often neck down at the sound barrier where drag is extremely high. As altitude increases within the aircraft's flight envelope the distance between lines of equal $P_s$ increase [Olson, 2000], this phenomenon also occurs once the aircraft goes supersonic which stretches the contour plot up and to the right of the speed altitude envelope. Figure (4) shows the 1-*g* energy maneuverability contour plots produced with the methods described in this paper. Visual inspection and comparison of figures (3) and (4) clearly show that methods used in determining the $P_s$ data not only faithfully mirrored the actual aircraft's values but showed the right characteristics expected in a fighter's energy maneuverability contour plot. Close scrutiny of the contour plots reveal a slight difference in $P_s$ values between the two plots. This discrepancy was found to be acceptable, especially due to the relative ease in which the data was produced and the ability to duplicate these results for many different platforms. Visual inspection of the energy maneuverability contour plots was performed on multiple aircraft, with all yielding similarly acceptable results.

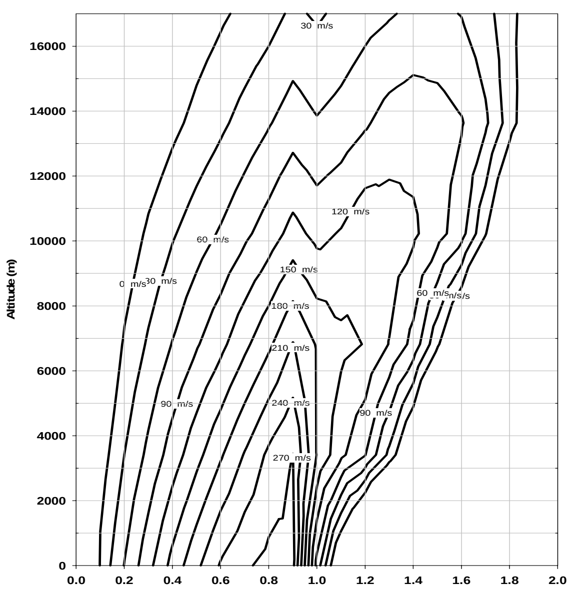


**Figure 4-** Energy Maneuverability Contour (1-*g*)

The next step in testing the performance of the aero-model was to fly the entities in XCITE, recording the positional and velocity data and then comparing these values against placard data points provided in the NASIC reports. These tests would evaluate not only the subroutines developed to control the entities but the raw $P_s$ data used as the foundation of the aero-model. Tests included straight line accelerations, maximum sustained level turns, maximum level speed, and maximum climb rate. These relatively simple 2-D maneuvers yielded very promising data. The results of these tests can be seen in Table (2) where the variance of performance parameters between NASIC data and the upgraded aero engine for several test points can be seen. Due to the classified nature of the data used to build the $P_s$ data for the Russian aircraft, the accuracy of the performance and not the actual performance figures is given.

**Table 2-** Variance in performance between Energy Maneuvers Model and NASIC data

| | F-16C | F/A-18C | Mig-29 | Su-27 |
|---|---|---|---|---|
| Max Velocity | | | | |
| 3,000 M | 3.6% | -5.0% | 0.0% | 0.0% |
| 6,000 M | 6.3% | 2.1% | 0.6% | 1.6% |
| 12,000 M | 4.8% | 1.2% | 8.5% | 14.1% |
| Acceleration | | | | |
| $V_{cruise}$-$V_{max}$ | -17.5% | 0.7% | -11.9% | -10.0% |
| Max Sustained G | | | | |
| Sea Level | 0.0% | 1.3% | 0.0% | 0.0% |
| 3,000 M | -11.5% | -19.2% | 1.9% | 4.4% |
| 6,000 M | 15.6% | -4.2% | 12.5% | 22.7% |
| Rate of Climb | | | | |
| Sea-Level | 11.9% | 5.6% | 4.1% | 1.3% |
| 11,000 M | 30.1% | -4.1% | 18.3% | 3.3% |

The final tests undertaken to test the new aero-model was to perform complex 3-D maneuvers, designed to test the bleeding and addition of energy, and compare this data to the output from a manned simulator. For these tests, XCITE provided a F-16C of the same load-out, weight, and configuration as the F-16 FMT. For familiarization, the FMT, piloted by a Subject Matter Expert (SME) with thousands of hours in the F-16, flew chase behind the XCITE entity as it flew multiple climbing, diving, turning, and accelerating maneuvers. Once the SME was comfortable with the rolling and pitching behavior of the XCITE entity he reproduced the same complex multi-planar maneuvers. While velocity and positional data was gleaned from both F-16s the SME provided useful critiques on the "look" and "feel" of the XCITE entity as it performed these maneuvers. Input from the SMEs indicated that the upgraded aero-model accurately accelerated and decelerated as the actual aircraft would in a series of different maneuvers. The SME also provided guidance on what combination of roll, pitch and bank would more closely mirror the way the aircraft are flown. Positional and velocity data from these tests of both F-16C aerodynamic codes provided the most solid data for comparison and analysis. The following figures compare the positional and velocity data of both the piloted F-16 FMT simulator and the XCITE entity controlled by the upgraded Energy Maneuverability aero-model.

The first test done with the F-16 FMT was maximum level acceleration at an altitude of 36,000 ft, Figure (5) illustrates the velocity profiles between the manned simulator and the upgraded energy aero-model in XCITE.

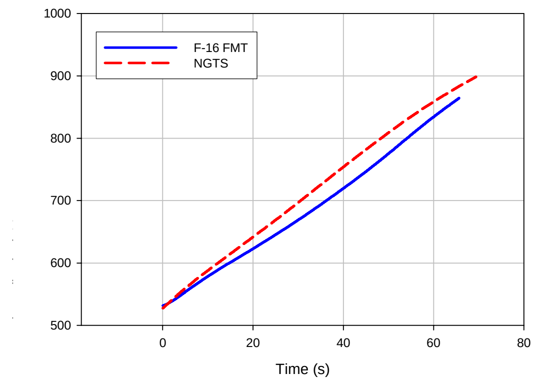


**Figure 5-**Velocity profile of a piloted F-16 FMT simulator and XCITE entity during level acceleration from Mach .93 to Mach 1.42

The next tests undertaken were level turns performed at differing load factors and altitudes. Figure (6) shows the flight path of both entities as they perform a 7-*g* turn at an altitude of 5,000 ft.

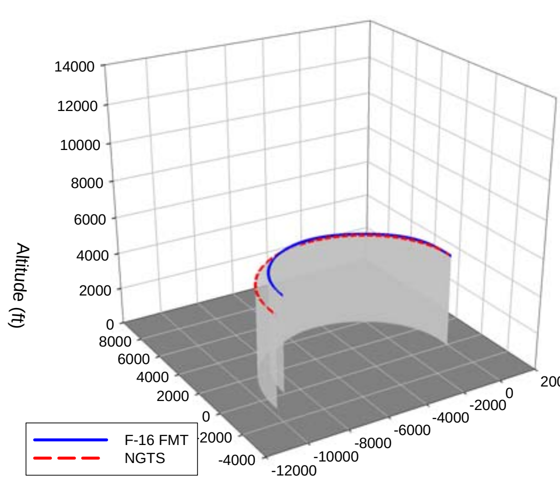


**Figure 6**- Flight path comparison between piloted F-16 FMT simulator and XCITE entity during a 7-*g* level turn at 5,000 ft

Figure (7) illustrates the velocity profile as both entities perform a 180 degree 7-*g* turn.

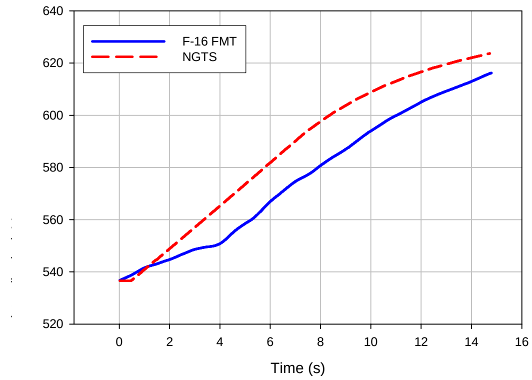


**Figure 7-**Velocity profile of a piloted F-16 FMT simulator and XCITE entity during a 7-*g* level turn at 5,000 ft

The next tests performed were climbing and diving tests designed to test how well the energy aero-model handled parsing up specific energy between climb rate and acceleration. Tests were done at a constant climb/ dive angle forcing acceleration based on available specific excess power after the desired climb has been achieved. Figures (8) and (9) show the flight path and velocity profiles of both the FMT and XCITE entities during a 30 degree dive.

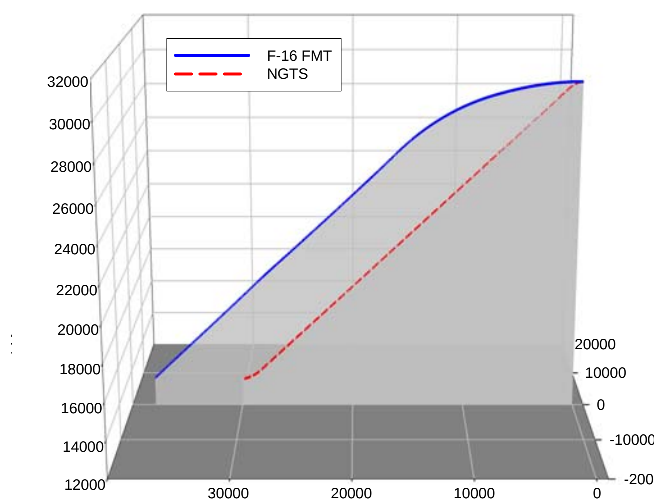


**Figure 8-**Flight path comparison between piloted F-16 FMT simulator and XCITE entity during a 30 degree dive

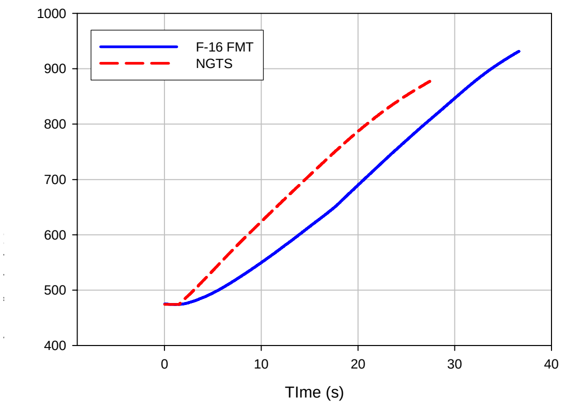


**Figure 9-**Velocity profile of a piloted F-16 FMT simulator and XCITE entity during a 30 degree dive

The last tests performed were designed to test how well the upgraded aero-model handled complex 3 dimensional maneuvers were the aircraft climbs, turns and accelerates at the same time. In Figure (10) the flight path of both manned simulator and XCITE entity are shown as they perform a pitchback maneuver.

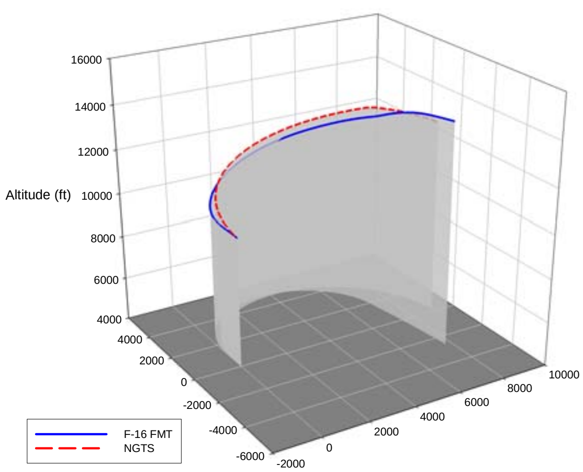


**Figure 10-**Flight path comparison between piloted F-16 FMT simulator and XCITE entity during a 4-*g* pitchback

Figure (11) illustrates the velocity profile of both entities during the pitchback maneuver.

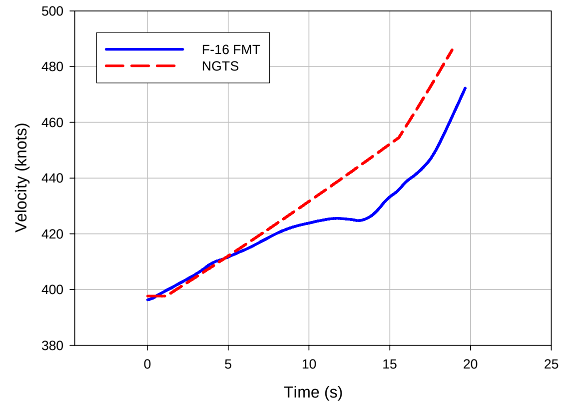


**Figure 11** - Velocity profile of a piloted F-16 FMT simulator and XCITE entity during a 4-*g* pitchback

Inspection of the preceding figures illustrates several important issues. In most every test performed there was a noticeable difference in the exact flight path between the manned simulator and the constructive entity. This is most evident on the level turns. Figure (12) illustrates how the load factor of the manned simulator varied throughout the turn and the constructive entity, as expected maintained a perfect turn. A manned pilot, no matter how experienced, will oscillate slightly above and below a desired load factor during a turn. When the load factor is above the desired level the aircraft bleeds energy, falling to a lower energy state and when the load factor is below the desired level the aircraft gains potential energy.

This behavior explains why the manned simulator usually lags slightly behind the XCITE entity in velocity and performs a slightly larger turn. This is seen in both the pitchback and the 7-*g* level turn.

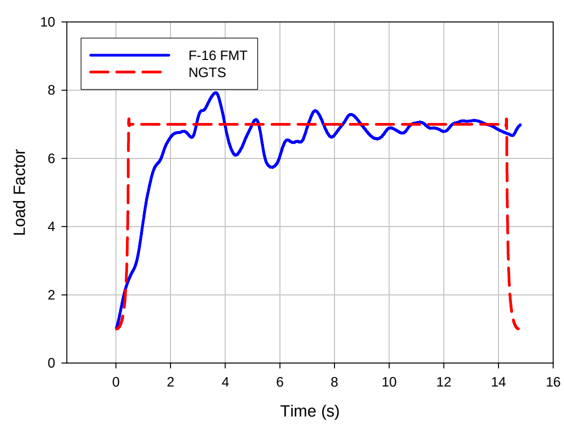


**Figure 12-** Variation in load factor between a piloted F-16 FMT simulator and XCITE entity during a 7-*g* level turn

Concerns over the way the XCITE entities entered and exited climbs and dives became a concern during testing. A manned aircraft would enter a dive at somewhere around 0.5-*g*'s as to not subject himself to excessive uncomfortable negative *g*'s, this behavior is evident in the gradual pitch-down seen in Figure (8). Also apparent is the crude method the current XCITE flight model both enters and exits some maneuvers, in this instance it does so in a unrealistic fashion.

In the process of performing these tests and analyzing the results we were quite satisfied with how well the upgraded aero-model matched the FMT in both turn performance and acceleration. Figure (5) illustrates how closely the velocities' matched during level acceleration. In fact, during the test, the XCITE entity stayed almost exactly the same distance in front of the manned simulator until maximum velocity was reached. In turns, climbs and accelerations velocity profiles closely matched between both aero-models. Figure (11) illustrates that even during a complex maneuver the upgraded energy based aero-model in XCITE provides accurate flight performance.

A strong correlation in performance is apparent between the energy maneuvers aero model and the full aerodynamic model found in the F-16 FMT. One must keep in mind that all the data taken from the FMT was subject to certain limitations. All inputs to the FMT came from a human pilot therefore there will always be slight variations and oscillations in not only load factor but altitude and other parameters such as roll and bank angles. The FMT used during these test had only one channel of video, forward out the window, and had a HUD setup on a separate monitor offset approximately 30° from center. Though the pilot became accustom to flying with the offset HUD, he did express that the lack of a 360° visual display had an affect on his ability to chase the XCITE entity during pitchback maneuvers

## 5.3 Limitations

The $P_s$ tables were created at a static weight and combat load configuration. The drag index is not necessarily representative of the constructive entity's current weapon load out but of a typical combat load and does not change as fuel is burned nor as weapons and stores are released from the aircraft. The $P_s$ tables are based on aircraft with a 50% fuel load. The static condition of the fuel and weapons load provides constructive aircraft at common aerial combat weights and configurations.

The upgraded aero-model was not intended as a perfect simulation of every aspect of flight dynamics. The model is not throttle-able, all the thrust data is for Max–AB. Thus, the energy based aero-model represents the maximum limits of performance but falls short on accurate representation of the non-max-AB flight regime. Affects such as engine spool-up and dynamic pitch and roll rates are not modeled in XCITE. The subroutine used to control maneuvers requiring accelerating, turning and climbing does work well in 2-D maneuvers such as level turns, straight accelerations and climbs, but requires much revision in order to accurately simulate maneuvers in which the aircraft climbs, turns and accelerates simultaneously.

All of the data used in creating the $P_s$ tables came from NASIC reports, some which dated back to the 1960s, throughout the years the format of the data represented in these reports has changed. Some of the reports are quite modern and clearly express the data pertinent for this project, while others required higher levels of interpolation. This matter came up when trying to copy thrust values. Some reports gave figures in Metric and others in English units, while the conversion is well known and straight forward, the NASIC thrust tables often reported thrust at multiples of 3,000 meters, which does not exactly match up with the intervals of 10,000 ft used in the $P_s$ data tables. This and other minor raw data translation and conversion issues may have an affect on the performance of the energy maneuvers flight model.

# 6 THE WAY AHEAD

In the beginning of the fiscal year AFRL started working with NASIC in a validation effort for XCITE. In the process of this validation effort the Aircraft Performance Branch offered assistance in creating higher fidelity $P_s$ data for the aircraft. Using HERCULES an internal 6-DOF NASIC model modified to provide data in the proper format, we are now able to insert validated NASIC data into XCITE. HERCULES easily allows various aircraft configurations, external stores load-outs, to be processed as well. With this additional capability we can create data sets for each aircraft in multiple configurations; clean (no external stores), full combat load, and a typical combat load. This added flexibility allows us to accurately model aircraft performance across an aircraft's entire mission.

As stated previously, more work is required to tweak the subroutines that control the entities. Specific Excess Power currently is not accurately parsed out between vertical velocity and flight-path acceleration. Once this "combination" maneuver has been improved, the interaction between this subroutine and the 37+ tactics within XCITE needs to be revisited in order to fine tune the behavior of several of the offensive and defensive tactics. Additionally, a more accurate representation of fuel consumption would allow fuel burn and fuel consumption to play a more viable part in tactics. Future efforts may look to incorporate behavioral models to allow entities to behave like pilots of various skill levels, possibly specific to the training and doctrine of individual threat countries. Development of the energy maneuvers aero-model upgrade occurred concurrent to many other upgrades to XCITE, notably the Instructor Operating System (IOS). Further work needs to be done to clean up the interface with the aero model through the IOS to enable operators to take full advantage of the aerodynamic upgrades.

## 7 CONCLUSION

The development and incorporation of the improved aero-model was a welcome addition to XCITE. With limited resources (the entire design, development, implementation, integration and testing was performed by the two authors) we were able to deliver a significant upgrade to the existing aero-model. Input from several F-16 SMEs on hand during testing indicates that the energy based aero-model "looks about right" in the way it bleeds and gains energy during maneuvers, quite an endorsement from a couple of retired Colonels with thousands of hours in the F-16. The impact the upgraded aero-model has on runtime performance and entity count was found to be negligible. The new aero-model merged nicely with the existing subroutine structure and tactics and only slight modifications to these subroutines were required. By fulfilling a critical requirement to provide accurate flight performance at low computational costs XCITE now provides a much improved training environment to the warfighter.

## 8 ACKNOWLEDGEMENTS

We would like to thank Mrs. Christine Covas for her help throughout the entire process of writing this paper; she walked us through all the steps necessary to get our work out to the masses. Mr. Craig Eidman provided not only technical help and expertise through the development of the aero-model but also flew the F-16 FMT during the performance testing and validation phase. Input and aid from Milt Miller, Kyle Tygret, Bob Feeman, Sam Hoefer, Dean Lewandowski, Glen Jolly, and Dave Lerman were crucial to the completion of this project; much thanks to all.

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## 10 BIOGRAPHY

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